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AN ELECTROMYOGRAPHIC STUDY OF THE ROLE OF THE ABDOMINAL MUSCLES IN BREATHING

By E. J. M. CAMPBELL

From the Middlesex Hospital Medical School, London, W. 1

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The mechanism of normal quiet expiration was described by Starling (1900) in Schafer's *Text-book of Physiology* in the following words: 'The diminution of the thoracic cavity which gives rise to expiration is under normal conditions not associated with the active contraction of any muscles. As the inspiratory muscles relax, the lung, in virtue of its elasticity, tends to contract and drag the chest wall with it. Moreover, the ribs which have been raised against gravity and the elastic resistance of the rib cartilages return to their previous condition, while the slack diaphragm is pushed up into the chest by the retraction of the abdominal walls pressing upon the abdominal viscera.' This account is still generally accepted. It is also generally supposed that expiration is assisted by muscular action when the volume of the breathing is increased or when the mechanism of elastic recoil is impaired.

Some of the unsettled problems of expiration in *man* are:

(1) Which are the expiratory muscles?

(2) What degree of respiratory activity can be achieved before they are brought into action?

(3) What pattern of activity do they show in relation to the phases of the respiratory cycle? Do they come into action early or late in expiration, or is the pattern variable?

The following partial answers are available to these questions.

(1) A consideration of the origin and insertion of the muscles (Bryce, 1923; Wood Jones, 1949; Johnston & Whillis, 1949) and the results of electrical stimulation (Duchenne, 1867) suggest that the chief muscles of expiration are those forming the anterior and lateral abdominal wall. When contracted these muscles raise intra-abdominal tension and therefore tend to drive the diaphragm upwards. The external and internal obliques and the rectus abdominis also draw the costal margin downwards and towards the midline.

As to the thoracic muscles, mechanical considerations (Hamberger, 1727) and animal experiments (Newell Martin & Hartwell, 1879; Bronk & Ferguson, 1935) suggest that those most likely to be expiratory in function are the interosseous portions of the internal intercostals. The sternocostalis is probably also expiratory in function (Wood Jones, 1949).

(2) There are no data concerning the volume or force of the respiratory movements that can occur before the muscles of expiration are brought into action in man; but Newell Martin & Hartwell (1879) and Gesell (1936) have made some semi-quantitative observations in animals.

(3) The relation of activity in these muscles to the phases of the respiratory cycle has been examined in animals by Gesell, Magee & Bricker (1940) but not in man.

In the experiments reported in the present paper the relation of the external oblique and rectus abdominis muscles to respiratory activity has been studied in man.

METHODS

The activity of the external oblique and rectus abdominis muscles was recorded electromyographically using needle electrodes.

A record of respiration was obtained by means of a spirometer whose excursions were registered on the electromyogram.

Apparatus

An Ediswan 4-channel amplifier with ink-writer oscillographs was used. The electrode needles were of 23 s.w.g. stainless steel hypodermic tubing coated to within 2–5 mm of the tip with wire enamel.

The spirometer was a water-filled 6 l. Kendrick model. A thread attached to the pulley was connected with a writing point; this gave a trace of the spirometer excursion on the electromyograph recording paper.

Subjects

Ten healthy young men aged 18–25 were studied.

Procedure

The subject lay supine on a couch with one pillow under his head, and occasionally with a similar support behind his knees. The skin and subcutaneous tissues were first anaesthetized with 2% procaine. The needle electrodes were then inserted obliquely through the anaesthetized areas into the muscles. Their points were at least 2 cm from the site of the anaesthetic, and the latter never interfered with the contraction of the muscle as judged from the electrical record.

Placing of the electrodes

External oblique. A pair of needles was placed in the flank in the anterior axillary line midway between the iliac crest and the costal margin. The needles were inserted obliquely 2·5–3 cm apart in the line of the fibres of the muscle.

Rectus abdominis. A pair of needles was inserted 2·5–3 cm apart into the main mass of the muscle. One of them was usually slightly above the level of the umbilicus and the other slightly below.

The muscles of the right side only were studied.

After the insertion of the needles the activity of the muscles was studied under the following conditions:

(1) Breathing quietly with the subject not attached to the spirometer.
(2) Raising the head from the couch.
(3) Lateral flexion of the trunk to the right.
(4) Making a voluntary maximal expiration.
(5) Making a voluntary maximal inspiration.
(6) Rebreathing from the spirometer to produce asphyxia.

The records

At the beginning of each experiment the electrical activity of the abdominal muscles was recorded when the subject was not using a mouthpiece and was not attached to the spirometer. Such records revealed the presence or absence of any resting activity and ensured that any respiratory variation observed in this activity was not due to the disturbance of the subject by a mouthpiece or spirometer.

The abdominal electrodes always pick up the e.c.g. which is a prominent feature of many of the records. The e.c.g. does not interfere with their interpretation and is, in fact, of value as a steady signal. Thus when movement artifact is considerable (usually when the respiratory excursions are markedly increased) the persistence of the e.c.g. in a section of tracing which shows no other electrical activity indicates that no muscular activity is taking place and that the electrical silence is not due to failure of the recording apparatus to function properly.

To avoid interference with the electromyograms the writing point of the spirometer tracing was arranged at a fixed distance (about 4 mm) ahead of (i.e. to the left of) the electrical record. The time interval corresponding to this displacement is given in the legends to the text-figures.

In this paper the record of the action potentials in the muscles is referred to as the electromyogram (e.m.g.).

RESULTS

Resting activity

The electromyogram recorded at the beginning of the experiment a few minutes after insertion of the needle electrodes into the muscles showed some activity in most subjects. The activity invariably became less marked as the experiment proceeded, and in most subjects it soon disappeared altogether (Fig. 3 *A–C*). It was liable to recur when the needle electrodes were adjusted and occasionally the threat of such an adjustment evoked it. It seemed that the activity was due to the subject's fear that the insertion or adjustment of the needles might hurt him. As his confidence was gained or his attention diverted from the electrodes the activity disappeared.

This 'resting activity' was more easily evoked in the external oblique than in the rectus abdominis. It was sometimes irregular and unrelated to the phases of respiration. However, the resting activity in four of the subjects did occasionally vary in relation to the phases of respiration. Fig. 5*B* illustrates the typical result, i.e. a decrease in activity during inspiration and an increase during expiration.

The effects on the electromyogram of movements of the head and trunk

The two movements employed consisted of raising the head off the couch, and lateral flexion of the trunk to the right. Fig. 1 shows that raising the head is associated with activity in the rectus but with little activity in the external oblique. Lateral flexion of the trunk, on the other hand, is associated with activity in the external oblique and little or none in the rectus. When these test manoeuvres during an experiment produce the kind of result just described, we can conclude that the electromyogram obtained from the rectus electrodes is not being seriously affected by the activity of the external oblique and that the electromyogram from the external oblique is similarly not being seriously affected by the activity of the rectus. To this type of result we apply the term 'good separation' of the two activity patterns.

As is shown subsequently, it is probable that the record obtained from electrodes in the rectus is due entirely to activity in that muscle. The electrodes in the external oblique, however, may also pick up activity from the underlying internal oblique and transversus abdominis.

In seven of the subjects 'good separation' was obtained. In the remaining three the difference between the records on carrying out the test movements was not as sharp as that obtained in the others. This 'poor separation' appeared to be due to the inability of the subjects to perform the movement of lateral flexion of the trunk without an associated raising of the head.

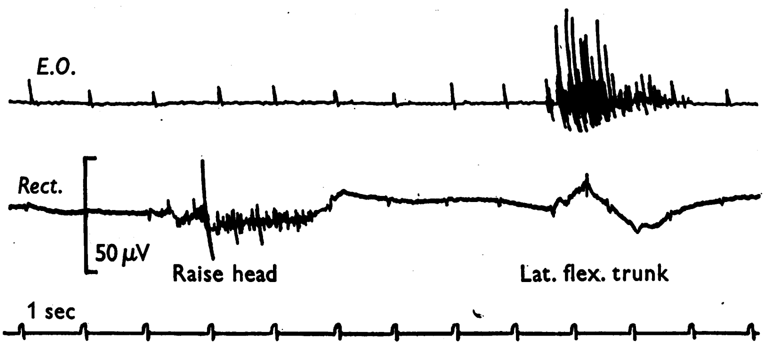

Fig. 1. The effects on the electromyogram of raising the head and lateral flexion of the trunk. Subject J.H. Records from above downwards; *E.O.*: the e.m.g. from a pair of needle electrodes in the right external oblique; *Rect.*: the e.m.g. from a pair of needle electrodes in the right rectus abdominis; time marker in seconds. Raising the head off the couch causes activity in the rectus abdominis but little in the external oblique. Lateral flexion of the trunk causes activity in the external oblique but little or none in the rectus abdominis.

The effects on the electromyogram of voluntary maximal inspiration and expiration

Fig. 2*A* illustrates an experiment in which a maximal inspiration was made steadily but not rapidly, held for 3 sec, and then released and followed by a maximal expiration.

The time taken to achieve full inspiration (3 l.) from the resting respiratory position was 4 sec; nearly $2\frac{1}{2}$ l. was inhaled during the first 2 sec. In the latter part of inspiration the rate of intake of air decreased and was associated with the appearance of progressively increasing activity in the rectus and external oblique. While the inspiration was maintained the activity remained at about its peak for 2 sec but then decreased until at the time of release of the breath there was almost none. During expiration there was no activity until the lung volume had almost returned to its resting level; activity then appeared and became increasingly pronounced until maximal expiration was achieved.

In these experiments the subjects were simply instructed to breathe out completely. In doing this they always slightly flexed the trunk. Floyd & Silver (1950) observed that if the subjects were instructed not to flex the trunk the rectus abdominis did not contract during maximal expiration or straining.

In the experiment illustrated by Fig. 2*B* the procedure was varied slightly. The subject inspired maximally as before, held the breath for 1 sec and then made a forced rapid maximal expiration. During the inspiration the record

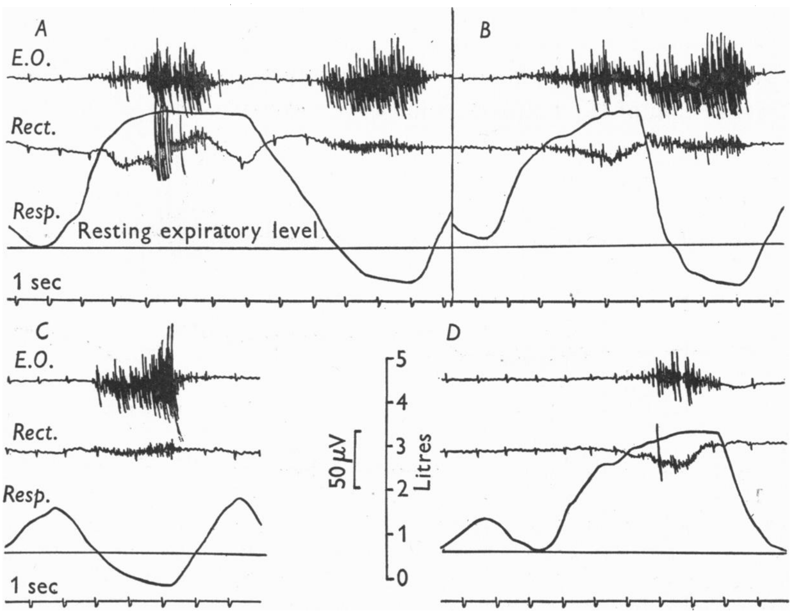

Fig. 2. The effects on the electromyogram of voluntary maximal inspiration and expiration. Subject G.M. Records in each case, from above downwards; *E.O.*: the e.m.g. recorded from a pair of needle electrodes in the right external oblique; *Rect.*: the e.m.g. recorded from a pair of needles in the right rectus abdominis; *Resp.*: the respiration recorded from a spirometer (inspiration upwards); time in seconds. The respiration record is $\frac{1}{4}$ sec to the left of the e.m.g.'s. *A*: inspiration held for 4 sec and released and then followed by a maximal expiration. *B*: forced expiratory effort made within a second of attaining full inspiration. *C*: maximal expiration made from resting expiratory position and followed by a normal inspiration. *D*: maximal inspiration followed by relaxation to the resting expiratory level and not followed by a maximal expiration. For the analysis of this figure, see text, p. 225.

resembles that seen in Fig. 2*A*. During the maintenance of inspiration activity persisted at a high level. At the onset of the sudden forced expiration there was no significant change in the activity. As the expiration proceeded the activity increased and reached its peak at the depth of the expiration. When the expiration was released activity rapidly declined and disappeared as in the previous experiment.

These results were found almost constantly in all subjects.

The following were the variations noted:

(i) *Usually* the activity at the end of inspiration was less marked than that occurring during expiration.

(ii) *Usually* the external oblique was more active both in inspiration and expiration.

When the maximal inspiration and the maximal expiration were performed separately (Fig. 2*C*, *D*) the onset and cessation of activity occurred at the same chest volume as that at which they occurred in Fig. 2*A*.

The effects on the electromyogram of progressive asphyxia

During the control period in some subjects there was irregular activity in one or other of the two muscles which was unrelated to the phases of respiration (Fig. 3*A*). Soon after the beginning of the experiment, as the breathing increased, there was a phasic diminution in the spontaneous activity during inspiration (Fig. 3*B*) and eventually it ceased altogether (Fig. 3*C*). In most subjects this activity was not prominent, and in many it did not occur at all. It is attributed to apprehension.

As breathing increased still further there was an occasional burst of activity in one of the muscles. This always occurred at the end of a deep expiration (Fig. 3*C*). Eventually this activity recurred with every expiration (Fig. 3*D*). The onset of this regular expiratory effort was always quite sudden and in any given subject bore a fairly constant relationship to the tidal volume and rate of breathing.

As the breathing increased during the final stages of the experiment the activity became increasingly marked and occurred progressively earlier in the expiratory phase (Fig. 3*E*).

When the experiment was ended by opening the valve on the mouthpiece to the room the activity continued to recur for several breaths. This shows that it was not due to the resistance to breathing offered by the spirometer (Figs. 3*E*, 4).

In some subjects activity occurred relatively early in the expiratory phase (Fig. 5), but always continued to the end of expiration and was always more marked in intensity if the expiration was deep. Thus in Fig. 5 the volume of air expelled in breath y was greater than in x but muscular activity was greater in x in which the terminal expiratory position was lower on the record than in y.

Some subjects completed expiration with a final increased effort which produced a 'dip' in the spirometer tracing (Fig. 4). This was always associated with muscular activity.

The relation of the time of onset of electrical activity to the rate and depth of respiration. Table 1 shows the rate and depth of ventilation at which one or other of the abdominal muscles was first 'recruited', i.e. brought into action in

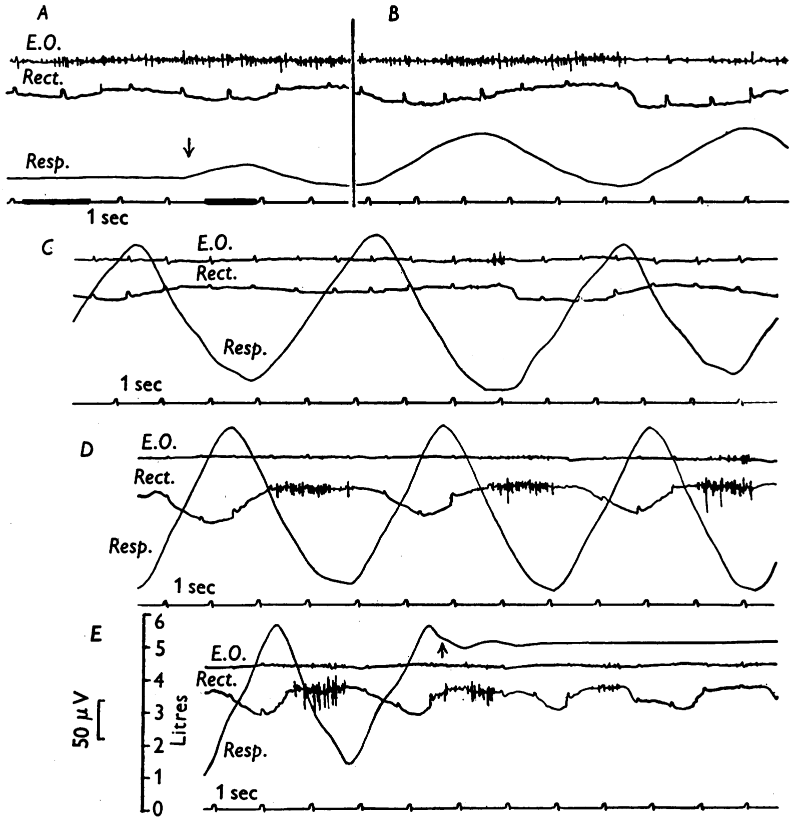

Fig. 3. The effects on the electromyogram of progressive asphyxia. Subject M.C. Records from above downwards; *E.O.*: the e.m.g. recorded from the right external oblique; *Rect.*: the e.m.g. recorded from the right rectus abdominis; *Resp.*: the respiration; time in seconds. The respiration record is ⅛ sec to the left of the e.m.g.'s. *A*: end of control period and beginning of experiment. The subject was breathing through a valve to the room. The signal on the time marker indicates the duration of inspiration as judged by an observer. At the arrow the valve was turned to connect the subject with the spirometer. There is spontaneous activity in the external oblique unrelated to the phases of respiration. *B*: six breaths (29 sec) after the end of *A*. There is an increase in the depth of breathing. Associated with this is a diminution of the spontaneous activity in the external oblique during inspiration. *C*: thirteen breaths (76 sec) after the end of *B*. There is no spontaneous activity. The only activity is a small burst in the external oblique at the end of the second expiration. This is the deepest of the three seen in the record. The pulmonary ventilation at this time was 44 l./min. *D*: four breaths (15 sec) after the end of *C*. Regular expiratory activity has appeared in the rectus abdominis and is beginning to appear in the external oblique. The pulmonary ventilation at this time was 60 l./min. *E*: five breaths (22 sec) after the end of *D*. It is the end of the experiment. At the arrow the valve was opened to the room. The phasic expiratory muscular activity is continued.

support of the passive mechanisms of expiration. The threshold of recruitment is the pulmonary ventilation at which contraction was regularly occurring as judged from the electrical record. The values are the average for the first five breaths during which phasic activity was constantly present. The experiment was repeated 2–5 times on each subject, and the volume given is the highest obtained for each subject. Relatively little variation was observed in spite

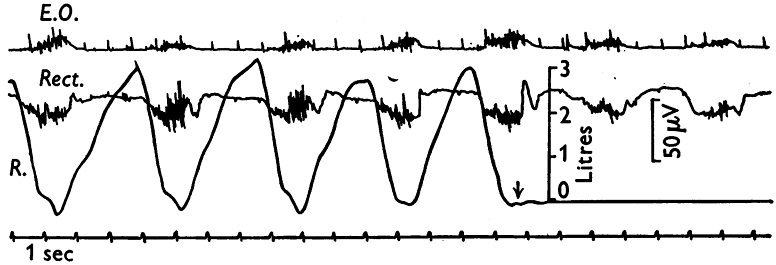

Fig. 4. The effects on the electromyogram of progressive asphyxia. Subject J.H. Records from above downwards; *E.O.*: the e.m.g. recorded from the right external oblique; *Rect.*: the e.m.g. recorded from the right rectus abdominis; *R.*: the respiration (inspiration upwards). Time in seconds. The respiration record is $\frac{1}{4}$ sec to the left of the e.m.g.'s. The subject had been rebreathing air from a 6 l. spirometer for 2 min before this record was taken. At the arrow the valve on the mouthpiece was opened to the room. There is well-marked expiratory activity in both muscles which continued during the recovery period.

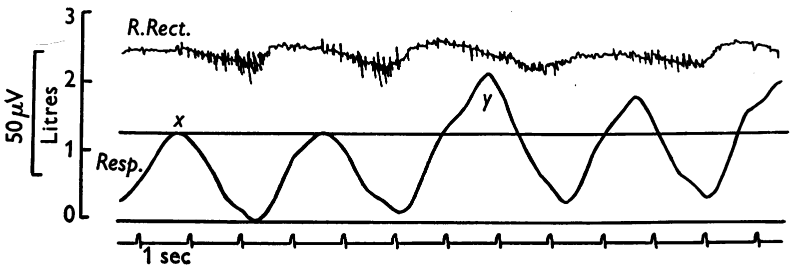

Fig. 5. The effects on the electromyogram of progressive asphyxia. Subject J.T. The records from above downwards are: *R. Rect.*: the e.m.g. recorded from the right rectus abdominis; *Resp.*: the respiration (inspiration upwards). Time in seconds. The respiration record is $\frac{1}{4}$ sec to the left of the e.m.g.'s. The amount of air expelled in breath x is less than in breath y, but the electrical activity is greater in x in which the final depth of expiration is greater.

of the difficulty of making quantitative observations of this kind. In apprehensive subjects when the experiment was first performed 'recruitment' appeared early; on repetition of the experiment with anxiety allayed, 'recruitment' was delayed until a greater increase in tidal volume appeared. It is evident from the table that the 'recruitment' of the external oblique and rectus is not related to the increase in rate, depth or total ventilation. It appears to be an individual peculiarity. Although the threshold varies so much between individuals it is, nevertheless, remarkable that a pulmonary ventilation of 45–65 l. can be attained before the abdominal muscles are brought into action.

How far are the electrical records fair samples of the activity of the two muscles?

With the electrodes arranged as described above, it is probable that activity of the muscle bulk in which they are placed will be recorded within a radius of several centimetres. It is not possible to estimate the range of pick-up accurately. This raises the following problems:

(i) Are the records fair samples of the activity of the whole of the muscle studied?

(ii) Does the contraction of other muscles contribute to the activity recorded?

TABLE 1. The relation of time of onset of electrical activity in the abdominal muscles to the rate and depth of respiration during progressive asphyxia.

(The values given for each subject are the averages for the first five breaths during which activity was constantly recurring. *E.O.* external oblique; *Rect.* rectus abdominis.)

Subject	Muscle predominantly 'recruited'	Level of respiration at which activity appeared			
		Critical tidal volume (l.)	Critical tidal volume expressed as % of vital capacity	Critical rate per min	Critical pulmonary ventilation (l./min)
1. M.C.	Both	4·5	80	13½	60
2. R.B.	Both	2·0	30	16½	33
3. G.M.	*E.O.*	1·5	30	20	30
4. D.F.	*E.O.*	2·4	55	8½	20
5. J.H.	Both	3·0	75	15	45
6. J.S.	*E.O.*	1·4	33	20	28
7. J.T.	*Rect.*	1·0	23	24	24
8. R.Y.	*E.O.*	1·2	33	20	24
9. D.A.	*E.O.*	2·5	40	27	65
10. M.G.	*E.O.*	1·3	30	14	18

(i) As the patterns of activity recorded in all the subjects were similar in relation to the phases of the respiratory cycle, it is probable that the relationships observed are reliable. It is, however, possible that quantitative estimates of the degree of respiratory effort at which activity first appeared in the muscles, like those presented in Table 1, are unreliable in that a more comprehensive exploration might show regional differences in the muscles. As there was such variation between the subjects and no common quantitative relationship was found, this does not matter very much.

In one subject, however, records were taken simultaneously from three separate parts of the external oblique with the following results:

(*a*) In all the manoeuvres described above to study the respiratory activity the different parts contracted in the same phases of the respiratory cycle.

(*b*) There was some variation in the intensity of activity at any moment in different parts of the muscle. The lower anterior part of the muscle was generally more active than the bulk of the muscle in the flank or the upper anterior part.

Similar studies were not carried out on the rectus abdominis, but Floyd & Silver (1950) found that records from one part were representative of the activity of the whole muscle.

(ii) The other muscles whose activity might be picked up are the diaphragm and the muscles of the posterior abdominal wall. In the case of the latter it is difficult on anatomical grounds to envisage any respiratory activity in them sufficiently intense to be recorded by the electrodes.

The diaphragm at its origin from the costal margin is within 5 cm of the electrodes in the external oblique, and in view of its bulk and importance as a respiratory muscle its possible role as a major contributor to the records must be carefully considered. That it can be excluded is probable for the following reasons:

(*a*) Even when the breathing is markedly increased no activity is recorded from the abdominal electrodes during inspiration at a time when the diaphragm is strongly contracting.

(*b*) The activity recorded at the end of maximal voluntary inspiration might at least in part be due to the powerful contraction of the fully descended diaphragm. However, if a submaximal inspiration was taken and then alternate inspiratory and expiratory efforts made against a closed glottis, the electrical activity was less intense during the inspiratory effort.

The internal oblique and transversus abdominis muscles probably contribute to the electrical record obtained from the external oblique. Anatomical considerations make it almost certain that they have the same respiratory functions as the external oblique so it does not matter if their activity is recorded.

DISCUSSION

These results confirm and amplify the classical account of the part the muscles of the abdominal wall play in breathing as outlined in the introduction. The muscles studied (rectus abdominis and external oblique) may be active under the following circumstances:

(1) When there is discomfort or fear of discomfort in them.

(2) During certain movements (head raising, lateral flexion).

(3) During the development and at the peak of a maximal inspiration. It is probable that this contraction of the abdominal muscles is one of the factors limiting the maximal inspiratory effort as suggested by Mills (1950). Whether the mechanism of this contraction is a reflex from the lungs, from the thoracic cage or from the abdominal muscles has not yet been determined. Although some activity occurs occasionally at the end of inspiration when the breathing is increased by asphyxia, it does not appear that contraction of the abdominal muscles is an important factor limiting the depth of inspiration under these conditions.

(4) During deep expiration whether made voluntarily or in response to asphyxia. It has been emphasized that the muscles are first recruited towards the end of expiration and that the force of their contraction increases as the expiration proceeds. According to Gesell *et al.* (1940) this pattern of activity does not occur in the expiratory muscles of dogs. They found that the pattern is either of the 'rapidly augmenting' or of the 'steady state' type. Pitts (1946) stresses that the 'rapidly augmenting' type of activity will ensure the rapid expulsion of air at the beginning of expiration. In man it would appear, however, that the abdominal muscles are more concerned with accelerating the *completion* of the expulsion of air at the end of expiration when the passive forces of recoil are decreasing to zero.

It is important to stress that these findings should not be extended to cover all the expiratory muscles, nor should they be taken as representative of the behaviour of the abdominal muscles in postures other than the supine.

SUMMARY

1. The external oblique and rectus abdominis muscles have been studied electromyographically in man, and their activity in various forms of breathing determined in the supine posture.

2. They were found to contract in the following circumstances: (i) during maximal voluntary expiration; (ii) during expiration when the volume of the breathing was increased by asphyxia; (iii) towards the end of voluntary maximal inspiration, but not during inspiration when the breathing was increased by asphyxia.

3. It is considered that contraction of these muscles is an important factor limiting the depth of voluntary maximal inspiration. It is not a factor limiting the depth of inspiration during hyperpnoea.

4. It is considered that these muscles complete expiration rather than initiate it.

5. A pulmonary ventilation of 40–60 l./min is possible before they are employed as accessory expiratory muscles.

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